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Soil carbon dioxide and methane fluxes from long-term tillage systems in continuous corn and corn–soybean rotations

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Abstract

Although the Midwestern United States is one of the world's major agricultural production areas, few studies have assessed the effects of the region's predominant tillage and rotation practices on greenhouse gas emissions from the soil surface. Our objectives were to (a) assess short-term chisel (CP) and moldboard plow (MP) effects on soil CO_2 and CH_4 fluxes relative to no-till (NT) and, (b) determine how tillage and rotation interactions affect seasonal gas emissions in continuous corn and corn–soybean rotations on a poorly drained Chalmers silty clay loam (Typic Endoaquoll) in Indiana. The field experiment itself began in 1975. Short-term gas emissions were measured immediately before, and at increasing hourly intervals following primary tillage in the fall of 2004, and after secondary tillage in the spring of 2005, for up to 168 h. To quantify treatment effects on seasonal emissions, gas fluxes were measured at weekly or biweekly intervals for up to 14 sampling dates in the growing season for corn. Both CO_2 and CH_4 emissions were significantly affected by tillage but not by rotation in the short-term following tillage, and by rotation during the growing season. Soil temperature and moisture conditions in the surface 10 cm were significantly related to CO_2 emissions, although the proportion of variation explained by temperature and moisture was generally very low (never exceeded 27%) and varied with the tillage system being measured. In the short-term, CO_2 emissions were significantly higher for CP than MP and NT. Similarly, mean seasonal CO_2 emissions during the 2-year period were higher for CP (6.2 Mg CO_2-C ha^{-1} $year^{-1}$) than for MP (5.9 Mg CO_2-C ha^{-1} $year^{-1}$) and NT (5.7 Mg CO_2-C ha^{-1} $year^{-1}$). Both CP and MP resulted in low net CH_4 uptake (7.6 and 2.4 kg CH_4-C ha^{-1} $year^{-1}$, respectively) while NT resulted in net emissions of 7.7 kg CH_4-C ha^{-1} $year^{-1}$. Mean emissions of CO_2 were 16% higher from continuous corn than from rotation corn during the two growing seasons. After 3 decades of consistent tillage and crop rotation management for corn and soybean producing grain yields well above average in the Midwest, continuous NT production in the corn–soybean rotation was identified as the system with the least soil-derived C emissions to the atmosphere from among those evaluated prior to and during corn production.

Keywords: Carbon dioxide emission; Continuous corn; Methane flux; Soil organic carbon; Rotation corn; Chisel plow; Moldboard plow; No-till

1. Introduction

Soil management practices are one of the major factors that can influence the soil–atmosphere exchange of greenhouse gases which contribute to global climate change (IPCC, 1996). Measurements of soil gas fluxes for different tillage treatments and cropping systems

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are, therefore, important for identifying management practices that can positively impact carbon (C) balance (Post et al., 1990; Reicosky et al., 1997) and greenhouse gas (GHG) emission. However, the magnitude and accuracy of determination of gas emission vary spatially (Rochette et al., 1991; Lessard et al., 1994) and gas emission itself is affected by such factors as seasonal climatic conditions (Mosier et al., 1996; Kessavalou et al., 1998), air and soil temperature (Parkin and Kasper, 2003), sampling frequency (Dugas, 1993; Parkin and Kaspar, 2004), and cropping systems (Drury et al., 2004). As a result of this extensive variability in C sequestration and emissions associated with changes in agricultural practices, the need to evaluate both short- and long-term emissions that are eco-region or soil-specific have been emphasized (Izaurralde et al., 2000; West and Marland, 2002).

Short-term effects of tillage and cropping systems on gas exchange between soil and atmosphere have been documented, albeit with varying results. In short-term experiments, Reicosky and Lindstrom (1993) and Reicosky (1997) reported greater CO_2 emissions for MP relative to CP and NT treatments in Minnesota. In Texas, Reicosky et al. (1997) found CO_2 emissions were greater for MP relative to CP and NT, and under bermudagrass compared to continuous sorghum. In more recent studies in Minnesota and Iowa, respectively, Al-Kaisi and Yin (2005) and Reicosky et al. (2005) found a relatively higher CO_2 emission for soils under MP than CP, strip- and deep-ripped, or NT systems in continuous corn and corn–soybean rotation systems. In contrast, La Scala et al. (2006) found that CO_2 emissions were about equal for CP and MP shortly after tillage, but that CO_2 emissions with CP declined, relative to MP, from days 2 to 27 after tillage. Similarly, in simulation studies Jacinthe et al. (2002a) found higher CO_2 emission for NT relative to CP and MP due to greater quantity of mineralizable organic carbon in no-till soils.

Relatively few studies have been conducted to evaluate long-term effects of tillage and rotation systems on greenhouse gas emissions. Curtin et al. (2000) found that CO_2 emission with NT was significantly less than for moldboard tillage, although tillage system differences were higher under continuous wheat than in wheat–fallow systems. Similarly, Dao (1998) reported a significantly lower CO_2 flux for NT than for MP, and that gas flux almost doubled within 60 days when crop residues were buried with MP. In a 3-year study where emission was measured all year round, Kessavalou et al. (1998) found higher CO_2 emission in native grasses (sod) relative to wheat–fallow rotation, as well as higher annual emission for MP relative to NT. Similarly, in a 2-year study involving measurements in multiple weeks, Bauer et al. (2006) reported a lower CO_2 emission for NT relative to conventional tillage (disc harrow followed by S-tined harrow smoothing).

Although methane (CH_4) has about 21 times the global warming potential of CO_2, and agriculture is believed to be responsible for about 27% of total CH_4 emission in the USA (Jawson et al., 2005), very few studies have involved field crop management impacts on CH_4. The majority of plant-based research efforts regarding CH_4 have been in forest soils (Castro et al., 1994; Goldman et al., 1995), in grasslands and their transition to cropland (Mosier et al., 1991), or in forests relative to croplands (Jacinthe and Lal, 2004). Tillage intensity can affect a range of biochemical properties but there is considerable uncertainty with regard to the impact of soil management practices on CH_4 uptake in agro-ecological systems (Jacinthe and Lal, 2005). Results from several studies suggest that cultivation may reduce CH_4 oxidation capacity of soils (Mosier et al., 1991; Bronson and Mosier, 1993; Lessard et al., 1994). In the Great Plains, Bronson et al. (1992) and Bronson and Mosier (1993) reported a 90% reduction in CH_4 oxidation capacity of tilled and irrigated soils under wheat and corn relative to native grassland soils. Kessavalou et al. (1998) found CH_4 uptake was highest in the spring, and for NT fallow relative to plowed winter wheat–fallow rotation. Similarly, Ball et al. (1999) indicated that CH_4 oxidation rate was highest for NT relative to MP treatments.

In the Midwestern USA where the corn–soybean rotation is the dominant cropping system (followed by continuous corn), NT accounts for more than 22% of production from all cropland area, and conventional tillage systems are used on more than 35% of cropland area (CTIC, 2004). Historically, the majority of the Midwestern fields not in NT or moldboard plowing systems have been chisel plowed. About 20.8×10^6 ha of poorly drained agricultural lands in the Midwest are tile drained (USDA-NRCS, 1987); improved drainage has benefited the adoption of conservation tillage.

While some studies have examined short-term CO_2 emissions (Reicosky, 1997; Reicosky et al., 1997; Al Kaisi and Yin, 2005), there are no reports available from this important agricultural region on the effects of tillage and rotation, and their interaction, on seasonal CO_2 emissions. Furthermore, since net CH_4 emission or uptake can be a delicate balance between oxidation and reduction that is dependent on soil saturation, the dynamics of CH_4 fluxes in artificially drained soils are largely unknown. Therefore, a broad objective in this study was to provide critically needed data for CO_2 and CH_4 fluxes that could help to improve modeling and prediction accuracy of soil gas emission for the Midwestern USA. The specific objectives were to assess (i) the short-term tillage intensity effects on CO_2 and CH_4 emissions, and (ii) the temporal variability in CO_2 and CH_4 fluxes from the soil surface during a crop growing season and how these emissions are related to tillage, rotation and their interactions.

2. Materials and methods

2.1. Site description and agronomic practices

This research was conducted in long-term tillage and crop rotation experimental plots located at the Purdue University Agronomy Center for Research and Education near West Lafayette, Indiana (40°28′N Lat.). The experiments were established in 1975 with the initial goals of analyzing long-term yield potential of different tillage systems in various crop rotations, and determining changes in soil characteristics and crop growth that could be associated with yield differences. Since time of establishment in 1975, moldboard plow, chisel, ridge, and no-till systems were compared in continuous corn, corn–soybean, soybean–corn, and continuous soybean rotations. Tillage system depths have been consistent since the trial began (20–25 cm for the moldboard plow and 15–20 cm for the chisel plow). The soil was developed under prairie vegetation, has less than 2% slope, and is a poorly drained Chalmers silty clay loam (fine, silty, mixed, superactive, mesic Typic Endoaquoll) but is tile-drained at 20-m intervals.

Cultural practices have been relatively consistent since the study began. No-till corn planting involved use of a single coulter to cut through the residues and loosen the soil ahead of standard planter units. Since 1997, tined row cleaners have been used in place of no-till coulters in front of the standard seed-disk openers. Lime (2.0 Mg ha^{-1}) was applied periodically to maintain soil favorable pH, but was last applied two years before these specific gas emission measurements were conducted. Starter N fertilizer was routinely applied at the rate of at 37 kg N ha^{-1} when corn was planted. Since 2001, nitrogen (N) was side-dress applied in June at the rate of 222 kg N ha^{-1} using 28% urea ammonium nitrate (UAN). Phosphorus and potassium fertilizers were periodically broadcast applied (either alone or in combination) before fall primary tillage operations to maintain adequate to high soil-test levels for these nutrients.

2.2. Experimental treatments

This study included no-till (NT), chisel (CP), and moldboard (MP) plow treatments in continuous corn (CC) and corn following soybean (rotation corn, RC). The experimental layout was a randomized complete block in a split-plot design with rotations as the main treatments and tillage as the subunits (randomized in rotations) with three replications. Each replicate consisted of plots that were 9 m wide, 45 m long (0.04 ha). Primary tillage treatments involving moldboard and chisel plowing were applied in fall of 2004 (November 11) and secondary tillage operations were carried out in spring of 2005 (April 18) just before planting. The moldboard plow treatment was applied using a commercially available International Harvester 5-furrow 46 cm semi-mounted moldboard plow. Moldboard plowing inverted the soil to a 22–25 cm soil depth, and without extensive breaking of soil aggregates. Chisel plowing was carried out using a DMI 7-shank coulter-chisel plow equipped with 10-cm twisted-shovel points on 37-cm centers and a Danish-tine sweep leveling bar. Secondary tillage operations for the MP and CP plots involved one pass of a tandem disk with spring-tooth harrows followed by a Glencoe field cultivator with C-shank sweeps and rear-mounted, double-rolling baskets; both operations were to a depth of approximately 10 cm. Following spring tillage operations, soil surface residue cover was 3% in MP and 31% in CP versus 93% in the undisturbed NT system. On April 19, 2005, corn was planted in 76-cm rows with a Case-IH model 955 row-planter. No-till CC was planted 15 cm beside the old corn rows using the unit-mounted row cleaners to clear the row area of residue when NT planting into corn and soybean residue.

For the study periods, daily and annual temperature and precipitation conditions are shown in Fig. 1. In 2004, highest cumulative monthly precipitations were recorded between March and June with peak rainfall in June. Mean annual temperature was 10.8 °C and total precipitation was 918.6 mm. In contrast, in 2005, much less than normal precipitation occurred from March to June and relatively higher than normal precipitation was observed from July to September. Although mean annual temperature was higher in 2005 (12.6 °C) than 2004, total annual precipitation in 2005 was much lower at just 560.7 mm.

2.3. Carbon dioxide and methane flux measurements

Tillage-induced soil surface CO_2 and CH_4 were simultaneously measured by the vented flux chamber

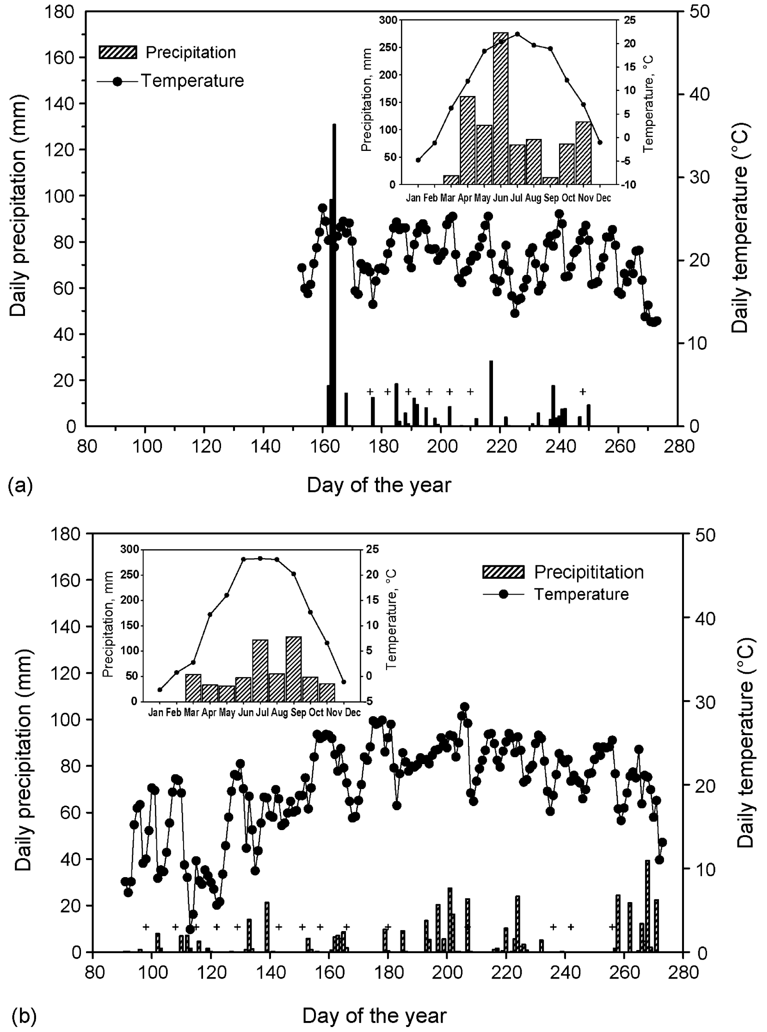

Fig. 1. Daily temperature and precipitation distribution in (a) 2004, and (b) 2005; inset is the cumulative monthly precipitation and mean monthly temperature distribution for the respective years; plus (+) sign refers to sampling date.

method (Mosier et al., 2006). In each measurement plot, duplicate anchors with inner dimensions measuring 73.7 cm × 35.4 cm × 12.0 cm capped with U-shaped channels (1.8 cm wide by 1.9 cm deep) welded to the outer-edge were driven about 10 cm into the soil. Within each plot, anchors were placed 10 m apart. A carpenter's level was used to ensure that the anchors were level. For short-term determination of the primary tillage effect, initial gas flux were taken before tillage and within a minute after tillage (referred to as time 0 h after tillage), and subsequently at 1, 2, 24, 48, 72 and 168 h after tillage. However, in the NT plots, gas fluxes were measured only at the 0 and 168 h time periods at the same time that measurements were taken from CP and MP treatments. Following secondary tillage, fluxes were also measured, but only at time 0 and 2 h after the tillage operation.

Gas fluxes were measured by placing vented chambers (volume = 32.4 l) over the anchors to cover the soil surface. To ensure that there was no gas exchange between chamber and atmosphere during sampling, the U-shaped channel of the anchor was filled with water to form an air-tight seal before sampling was begun. Samples were then collected from the chambers through a rubber septum at regular intervals of 0, 5, 10, and 15 min after deployment using a 20 ml polypropylene syringe and pressurized into pre-evacuated vials (12 ml Exetainer, Labco, High Wycombe, UK). The 15 min time period for gas sampling was chosen as convenient because Jury et al. (1982) recommended that a time frame of <60 min be used to accurately estimate gas fluxes under aerobic conditions.

For the seasonal tillage effects and temporal variability assessment, gas samples were collected weekly during the growing season. In the 2004 growing season, gas sampling was carried out in seven measurement periods beginning in June 23 (approximately 8 weeks after secondary tillage; 6 weeks after planting) and ending September 4, 2004. During the 2005 growing season, sampling was carried out for 14 weeks beginning on April 8 (1 week before secondary tillage) and continued through September 13. Because of inclement weather conditions and resource constraints, sampling was not done in the month of July.

Kessavalou et al. (1998) reported a significantly higher gas emission from crop rows relative to inter-rows. Therefore, to reduce variability between measured and actual emissions in the growing season sampling period, anchors were placed perpendicular to rows from approximately the 1/4 inter-row to approximately the 3/4 inter-row positions on the opposite side of the same row to insure that our gas sampling captured both the row and inter-row areas. However, all plants that were within the chamber were clipped at soil level at all times during sampling. Anchors were kept in the same positions through the course of the experiment and all sampling were carried out between 10 a.m. and 12 noon of each sampling date. Soil moisture was determined using a TRIME-TDR to a depth of 10 cm, and soil temperature recorded with a thermometer to 7 cm soil depth at time of gas sampling for each chamber position.

The concentrations of CO_2 and CH_4 in the samples were determined using a gas chromatograph (Varian 3800 GC, Mississauga, Canada) equipped with an automatic Combi-Pal injection system (Varian, Mississauga, Canada) that was described in detail by Drury et al. (2004). Briefly, gas samples were automatically injected into the chromatograph using the Combi-Pal sampler. The sample was passed through a 1.83 m Porapak N column in a 50 °C oven with grade A helium as carrier gas, flowing at 30 ml min^{-1} and CO_2 was analyzed with a thermal conductivity detector set at 130 °C, and a flame ionization detector for CH_4. Gas fluxes were calculated from the rate of change in chamber concentration, chamber volume, and soil surface area using the formula of Hutchinson and Mosier (1981). Chamber gas concentration was converted from molar mixing ratio unit of parts per million (ppm) determined by GC analysis to mass per volume units assuming ideal gas relations (Venterea et al., 2005).

2.4. Statistical analysis

Statistical analysis of the data was performed using the General Linear Model using SAS (SAS Institute, 2002) with rotation as main plots and tillage as subplots. Since the underlying objective of the study was to assess the possibly interacting effects of tillage and rotation practices on greenhouse gas emissions, statistical analyses were done in stages for the gas emission data. First the data was analyzed to determine effects of rotation, tillage, and rotation × tillage effects, separately for short-term and seasonal emissions. Preliminary analyses indicated that in the short-term, both CO_2 and CH_4 fluxes were significantly affected by tillage, but rotation treatments and rotation × tillage interactions affected only CH_4 fluxes. However, for the seasonal emission data, rotation had significant effects on gas fluxes while neither tillage nor tillage × rotation interactions had any significant effect on CO_2 and CH_4 fluxes. Given the complexity of the treatment effects, the data was separated and analyzed separately as tillage and rotation effects by averaging tillage effects over rotation treatments, and rotation effects over tillage treatments, where tillage or rotation was significant. Because gas flux rates were measured repeatedly over time from the same spot, analysis of variance for split-plot experimental design over time and space was computed using the general linear model where rotation and tillage effects were considered random and time of measurement was considered fixed. Treatment means were separated using least significant difference (LSD) and the effects of rotation and tillage on gas fluxes were evaluated at the 5% level of probability ($\alpha = 0.05$). Furthermore, linear regression models were used to evaluate the relationships between these trace gases and soil moisture and temperature.

3. Results

3.1. Carbon dioxide fluxes

Carbon dioxide emissions were significantly affected by primary tillage (CP and MP) but emissions from these treatments were not different following secondary tillage operations (Table 1). Similarly, CO_2 emissions were not significantly influenced by rotation or the rotation × tillage interaction following both primary and secondary tillage treatment application. In general, CO_2 emissions due to primary tillage varied widely with treatment and time of measurement (Fig. 2a). Emissions were greater immediately after tillage (at 0 h) but declined sharply within hours after tillage operations

Table 1
Statistical significance of tillage, rotation and tillage × rotation interaction effects on short-term and growing season emission of soil carbon dioxide and methane in 2004 and 2005 growing seasons

Source	$P > F$	
	CO_2	CH_4
Primary tillage		
Rotation	0.6760	0.0312
Tillage	0.0001	0.0115
Rotation × tillage	0.8753	0.0044
Secondary tillage		
Rotation	0.2886	0.0678
Tillage	0.1969	0.1491
Rotation × tillage	0.5313	0.2588
2004 growing season		
Rotation	0.0206	0.9112
Tillage	0.0898	0.5215
Rotation × tillage	0.3815	0.7960
2005 growing season		
Rotation	0.0185	0.6905
Tillage	0.3066	0.1464
Rotation × tillage	0.4216	0.7734

and, for both tillage systems, reached their lowest intensity 72 h after tillage. Across treatments, CO_2 emissions at 0, 1 and 2 h were significantly greater than for the 24–168 h following tillage (Fig. 2) but were similar to emissions before tillage. In general, post primary tillage CO_2 emissions were consistently greater for CP (mean: 0.03 g CO_2-C m^{-2} h^{-1}) than for MP (mean: 0.01 g CO_2-C m^{-2} h^{-1}). Similarly, secondary tillage also increased CO_2 fluxes relative to before application. However, emissions from CP treated plots decreased sharply, but increased linearly for MP 2 h following secondary tillage (Fig. 2). Compared to NT, CO_2 emissions were about 74.5 and 53.4%, respectively, higher from CP and MP treatments but only at 0 h following primary tillage application (Fig. 2).

Seasonal CO_2 fluxes measured during the 2004 and 2005 growing seasons were temporally variable (Figs. 3 and 4) and were significantly affected by rotation but not by tillage or tillage × rotation interaction. Although tillage treatment effects were not generally significant, in 2004 significant difference of emissions was observed for CP and MP relative to NT in mid July, and in early May of 2005 (Fig. 3). Average seasonal CO_2 emissions for CP (0.09 g CO_2-C m^{-2} h^{-1}) was 3 and 11% higher than for NT and MP, respectively, in 2004 and was (0.06 g CO_2-C m^{-2} h^{-1}) 4 and 11% higher than MP and NT, respectively, in 2005. Seasonal CO_2 emissions were significantly greater under CC than for RC in both 2004 and 2005 growing seasons. In 2004, CO_2 emissions under CC ranged from 0.06 to 0.13 g CO_2-C m^{-2} h^{-1} and from 0.05 to 0.10 g CO_2-C m^{-2} h^{-1} under RC. Similarly, emissions ranged from 0.02 to 0.11 g CO_2-C m^{-2} h^{-1} for CC and from 0.01 to 0.09 g CO_2-C m^{-2} h^{-1} under RC in the 2005 (Fig. 4). In both years, emissions during the growing season were highest during the month of June and this coincided with the period when organic matter mineralization was

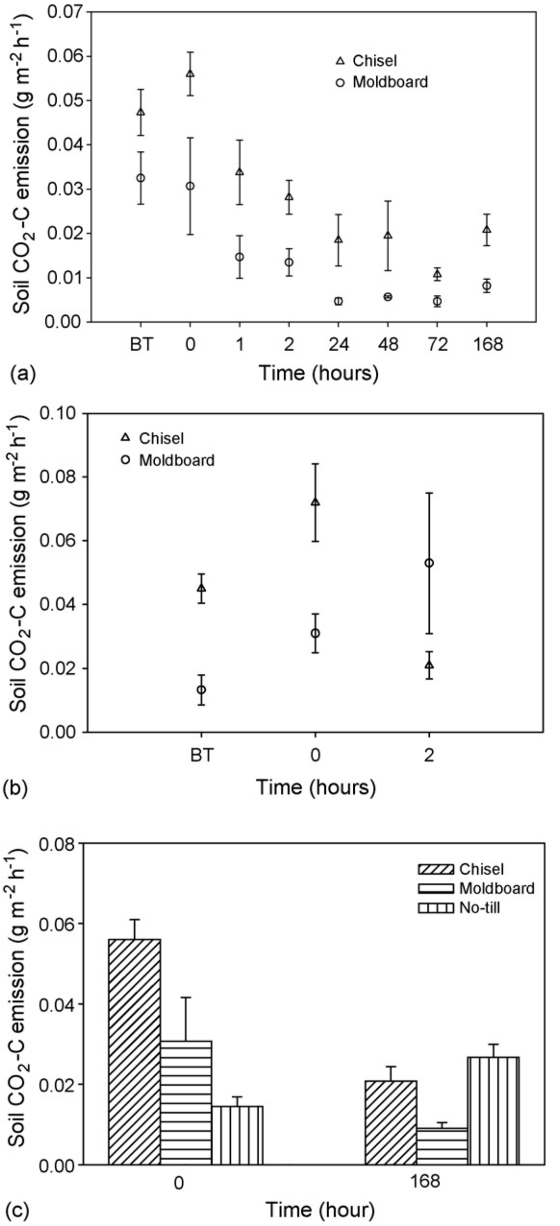

Fig. 2. Short-term (hourly) carbon dioxide emissions due to (a) fall chisel and moldboard plow primary tillage operations, (b) secondary tillage of chisel and moldboard tilled plots and (c) emissions for chisel and moldboard relative to no-till measured at 0 and 168 h. ‘BT’ refers to before tillage; error bars are standard deviations of the means.

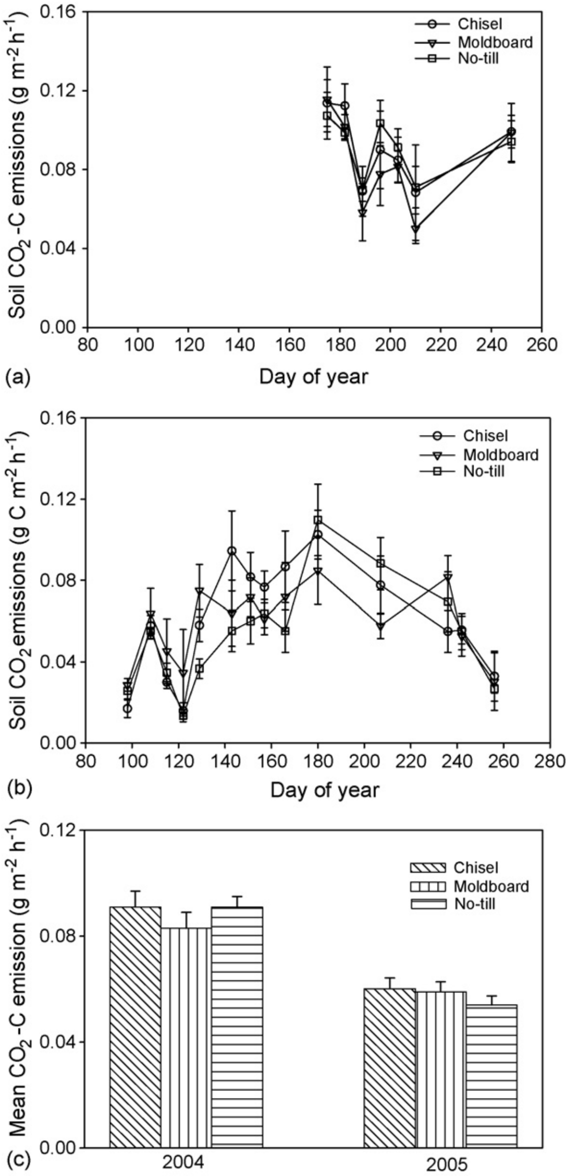

Fig. 3. Long-term weekly soil carbon dioxide emissions as affected by tillage treatments in (a) 2004, (b) 2005 growing seasons and (c) average emissions during 2004 and 2005 growing seasons; DOY refers to day of the year emissions were measured. Error bars are standard deviations of the means.

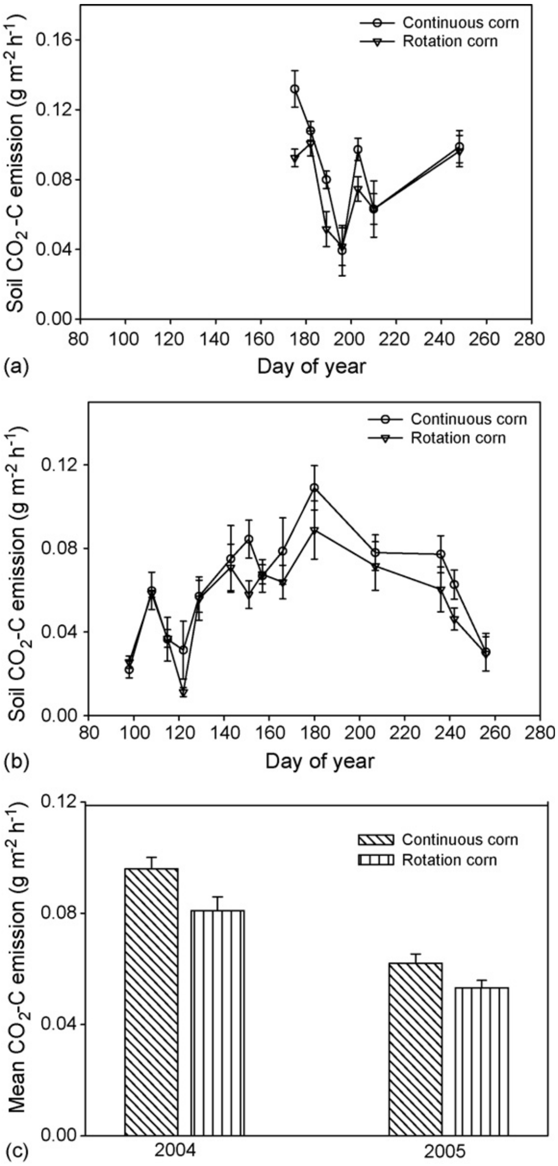

Fig. 4. Long-term weekly soil carbon dioxide emissions as affected by rotation in (a) 2004, (b) 2005 growing seasons and (c) average emissions during 2004 and 2005 growing seasons; DOY refers to day of the year emissions were measured. Error bars are standard deviations of the means.

expected to peak (Fig. 4). Although estimated corn plant biomass and biomass C returned to soil (Prince et al., 2001) over the past 30 years was greater for RC than for CC (when both treatments are in corn), and soil residue cover was greater for CC than for RC after tillage (Table 2), average seasonal emissions were about 16% higher for CC than for RC in both 2004 and 2005 growing seasons.

3.2. Methane fluxes

Methane fluxes following primary tillage treatment were generally low (i.e. averaged close to zero) but were significantly affected by both tillage and rotation, and their interaction. Although numerically small, tillage operations resulted in negative CH_4 fluxes on the majority of sampling dates (Fig. 5.); negative fluxes

Table 2
Tillage effects on 30-year average corn grain yield (1975–2004), estimated plant biomass and biomass carbon, and soil residue cover after tillage operations in continuous corn and rotation corn

Tillage	Rotation						Residue cover after planting			
	Continuous corn			Rotation corn			Continuous corn		Rotation corn	
	Grain yield	Biomass[†] (Mg ha^{-1})	Biomass C[‡] (Mg ha^{-1})	Grain yield (Mg ha^{-1})	Biomass (Mg ha^{-1})	Biomass C (Mg ha^{-1})	2004 (%)	2005 (%)	2004 (%)	2005 (%)
Moldboard	10.6a	16.9	7.1	11.1a	17.8	7.5	4	3	2	2
Chisel	10.4b	16.5	6.9	11.2a	17.8	7.5	31	32	9	13
No-till	9.2c	14.7	6.2	10.9b	17.4	7.3	93	87	85	77

Figures in column followed by the same letter are not statistically significant from each other at $P = 0.05$.

[†] Aboveground biomass estimated on a dry matter basis from grain yield at 15.5% moisture assuming 53% harvest index.

[‡] Biomass carbon calculated as 0.42% of plant biomass.

were indicative of a net CH_4 uptake for these soils. Following tillage treatments, CH_4 emission from CP increased rapidly from a negative flux value of −0.002 to a net emission value of nearly 0.001 mg CH_4-C m^{-2} h^{-1}. The overall flux pattern from MP was relatively unchanged during this brief measurement period. In general, short-term CH_4 emissions were reduced under CP and MP by more than 100% at 0 and 168 h after tillage relative to NT (data not shown). Similarly, average CH_4 emissions were significantly greater for RC than for CC (Fig. 5).

Seasonal CH_4 fluxes were not significantly affected by tillage, rotation or their interaction although fluxes varied widely with treatments and time (Fig. 6).

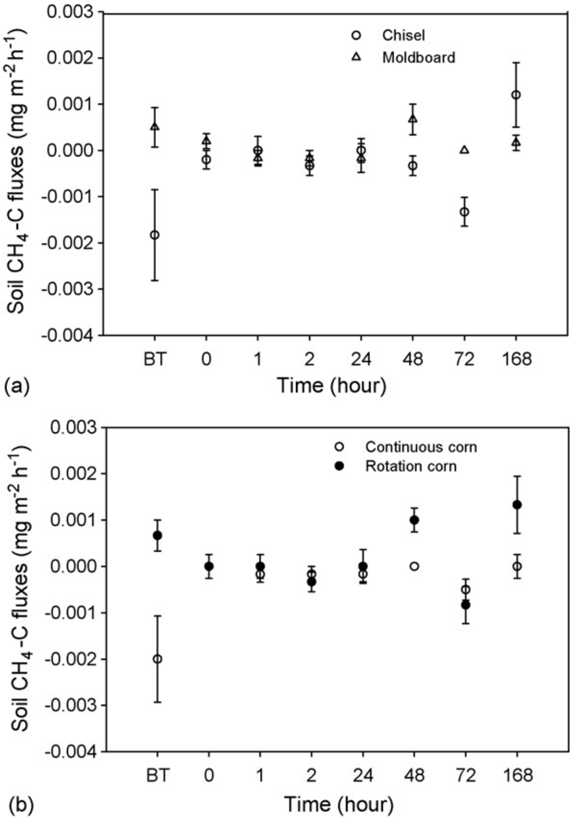

Fig. 5. Short-term hourly methane fluxes associated with (a) fall chisel and moldboard tillage, and (b) rotation systems. 'BT' refers to before tillage; error bars are standard deviations of the means.

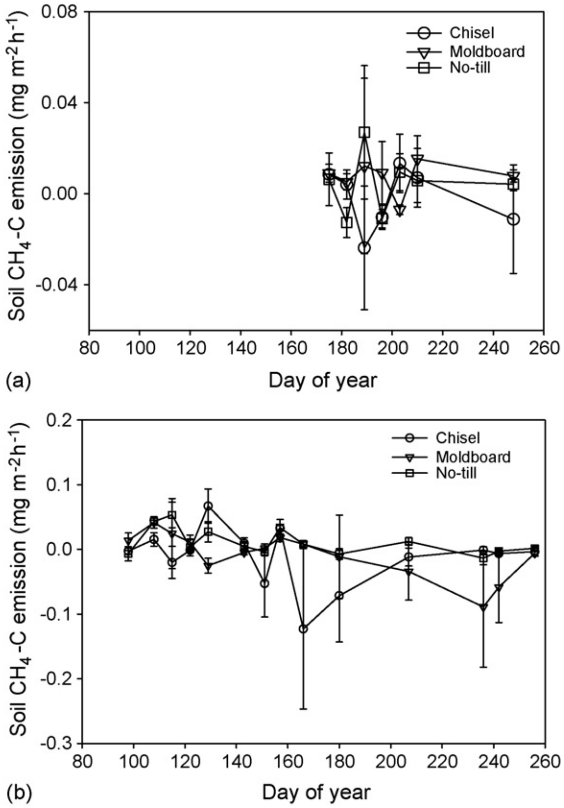

Fig. 6. Long-term weekly soil methane fluxes due to tillage treatments in the growing seasons of (a) 2004, and (b) 2005; DOY refers to day of the year emissions were measured. Error bars are standard deviations of the means.

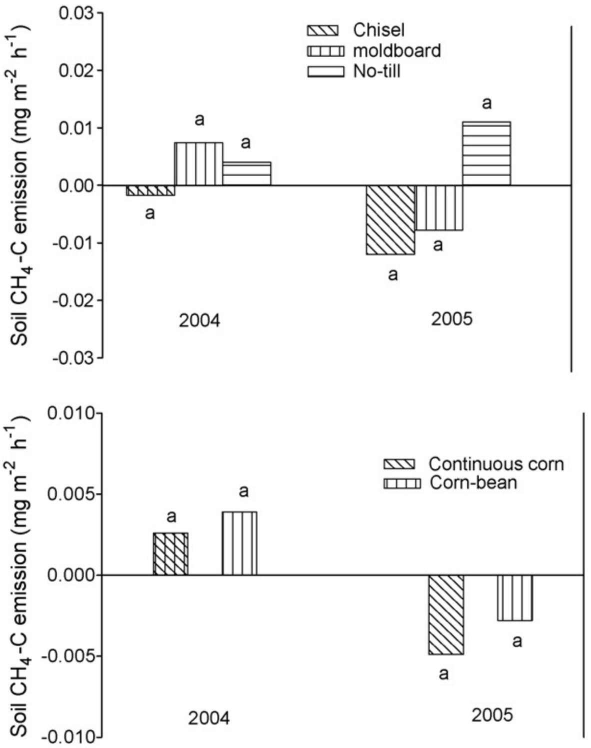

Fig. 7. Seasonal average methane emissions for tillage and rotation systems in the growing seasons of 2004 and 2005. Bars that are followed by the same letters are not significantly different.

Emissions were numerically greater for NT and least for CP. On average, MP and NT resulted in net emission (0.007, and 0.004 mg CH_4-C m^{-2} h^{-1}, respectively) while CP resulted in a net CH_4 uptake (−0.002 mg CH_4-C m^{-2} h^{-1}) in 2004. In 2005, both CP and MP treatments resulted in net CH_4 uptake (CP = −0.012; MP = −0.009 mg CH_4-C m^{-2} h^{-1}) and NT consistently resulted in net emission (0.011 mg CH_4-C m^{-2} h^{-1}). Similarly, CH_4 fluxes were positive under CC and RC rotations in 2004, but were negative for both rotations in 2005 (Fig. 7). In general, soil CH_4 emission was in the order CP < MP < NT and was greater under RC than CC.

3.3. Soil temperature and moisture effects on gas fluxes

Linear regression analyses relating fluxes to soil temperature and moisture in each treatment are shown in Table 3. Soil CO_2 emissions were significantly affected by soil temperature and moisture even though CO_2 emissions responded differently to temperature and moisture depending on tillage treatments and time of gas sampling (Table 3). However, CH_4 fluxes were not affected by either temperature or moisture (data not shown). In the short-term emission studies, soil temperature and moisture significantly influenced CO_2 emission from soils under MP ($R^2 = 0.17$), but not CP. Similarly, in the 2004 growing season the effects of soil moisture on CO_2 emissions were highly significant ($P = 0.003$) and accounted for 21 and 16% of variability in emissions for NT and MP, respectively. In contrast, 2005 growing season emissions for all three treatments were significantly related only to soil temperature (R^2: NT = 0.26; CP = 0.27; MP = 0.01). However, the mean soil moisture concentrations at sampling were much higher in 2005 than in 2004 (Table 3). The results further indicated that soil moisture appeared to be the greater factor influencing gas emissions in NT and MP plots while temperature had greater influence on gas emissions from CP. Across all tillage treatments, there was a significant but weak relationship between CO_2 emission and soil temperature ($R^2 = 0.18$) and between emission and soil moisture ($R^2 \leq 0.13$).

4. Discussion

Our results clearly indicated that CO_2 and CH_4 fluxes were significantly affected by tillage treatment in the short-term following primary tillage operations, but growing season CO_2 emissions were influenced mainly by rotation. Although, these management systems have no effect on seasonal CH_4 fluxes, tillage effects on CH_4 fluxes were discussed further giving the unique soil moisture conditions, and because previous there are no data on long-term tillage effects on CH_4 emissions for croplands in the Midwest.

4.1. Soil hydro-thermal condition affecting CO_2 fluxes

The generally low association of CO_2 emission with soil temperature and moisture reported in this study was consistent with other reports from tillage experiments from the Midwest and the Great Plains of the USA (Al-Kaisi and Yin, 2005; Kessavalou et al., 1998). In this study, low or non-significant effects of soil temperature on emission were attributed to the prevalence of either low temperatures (November 2004) or relatively small ranges in soil temperatures during the measurement period (June–August 2004). In contrast, the significant relationship between emissions and temperature in 2005 were probably due to the earlier onset of gas emission measurements in the growing season that year and the relatively higher and wider range of soil

Table 3
Regression models of relationships between soil carbon dioxide emission and soil temperature and moisture in no-till, chisel and moldboard plow treatments both in the short-term and during 2004 and 2005 growing seasons

Tillage treatment	Mean soil temperature (°C)	Mean soil moisture (mm)	Regression model	R^2	$P > F$
Short-term					
CP	10.3		$1916.99 - 28.91T_{\text{soil}}$	0.02	ns
		22.8	$658.06 + 42.06M_{\text{soil}}$	0.03	ns
MP	9.8		$-744.88 + 42.06T_{\text{soil}}$	0.13	0.016
		19.9	$-530.14 + 66.8M_{\text{soil}}$	0.17	0.004
Long-term (2004)					
NT	23.5		$4682.11 + 18.9T_{\text{soil}}$	0.003	ns
		31.9	$2008.8 + 99.02M_{\text{soil}}$	0.21	0.003
CP	23.9		$10604.07 - 223.6T_{\text{soil}}$	0.04	ns
		30.7	$440.95 + 32.64M_{\text{soil}}$	0.02	ns
MP	24.1		$4656.57 + 0.99T_{\text{soil}}$	0.006	ns
		29.1	$2609.93 + 73.74M_{\text{soil}}$	0.16	0.009
Long-term (2005)					
NT	21.1		$-29.0 + 152.05T_{\text{soil}}$	0.26	0.001
		39.3	$4193.2 + 28.45M_{\text{soil}}$	0.06	0.021
CP	22.1		$-61.03 + 159T_{\text{soil}}$	0.27	0.001
		41.4	$3115.98 + 9.34M_{\text{soil}}$	0.005	ns
MP	22.4		$1886.97 + 66.16T_{\text{soil}}$	0.06	0.03
		37.5	$2773.07 + 15.13M_{\text{soil}}$	0.02	ns

T_{soil}: soil temperature; M_{soil}: soil moisture.

temperature when measurements spanned from spring to summer periods. On the other hand, the lack of relationship between soil moisture and emissions in 2005 was probably due to the timing of precipitation events relative to gas emission measurements. We note that monthly mean precipitation during the growing season was lower in 2005 than in 2004 (Fig. 1), and yet mean soil moistures at the time of sampling were higher in 2005 than in 2004 (Table 3).

Although the importance of soil physical factors on microbial activity, root activity and gas diffusivity is generally acknowledged (Howard and Howard, 1993; Kirschbaum, 1995; Follett, 1997; Smith et al., 2003), the specific impacts of soil moisture and temperature on gas emissions from the soil surface are still uncertain. However, similar to our results, Kirschbaum (1995) and Follett (1997) reported that soil temperature was the primary factor governing CO_2 emission in studies that spanned an entire growing season or 12 months. In a review of the interacting effects of soil physical factors and biological processes on soil–atmosphere gas exchange, Smith et al. (2003) concluded that CO_2 release by aerobic respiration is primarily temperature dependent, but becomes moisture-dependent as a soil dries. Smith et al. (2003) also emphasized the importance of depth and time (diurnal) of soil temperature measurement on the relative temperature association with CO_2 emission from soil. Our present results demonstrate that both soil temperature and moisture were significantly related to emission (depending on the time of measurement), but the unique observation in our study was that the relative importance of temperature or moisture on gas emissions varied with the tillage system being measured.

4.2. Soil management-induced CO_2 fluxes

Tillage-induced CO_2 emission values reported here were consistent with those reported for short-duration experiments in parts of the Midwest (Reicosky et al., 1997, 2005; Al-Kaisi and Yin, 2005), and elsewhere (Dao, 1998; Rochette and Angers, 1999; Frank et al., 2006). Similarly, significantly greater CO_2 emissions immediately following tillage operations relative to emissions before tillage was consistent with the reports of Reicosky and Lindstrom (1993), Reicosky et al. (1997), and Al-Kaisi and Yin (2005) and was attributed to rapid physical release of CO_2 trapped in the soil air space due to soil physical disturbance (Reicosky and Lindstrom, 1993; Jackson et al., 2003). However, differences of emission between MP and CP tended to persist longer than was previously reported (Reicosky et al., 1997; Al-Kaisi and Yin, 2005) for short-term studies (i.e. for about 72 h after the initial tillage operations). Similarly, greater tillage-induced CO_2 emissions for CP relative to MP were in sharp contrast to the results of Reicosky and Lindstrom (1993), Reicosky (1997), and Reicosky et al. (2005) who attributed higher emission in MP to greater soil volume that was disturbed under MP relative to CP. One major factor for the observed differences may be the timing of MP and CP primary tillage operations. In this study, moistures of this fine-textured, high organic matter soil (Gál et al., submitted for publication) were relatively high and air temperatures relatively low (range: 7–13 °C) when MP disturbance was imposed; furrows remained relatively intact in the inversion process and little aggregate or clod dispersal was observed. In contrast, Reicosky (1997), and Reicosky et al. (2005) compared MP and CP close to the summer period (August/September) when air temperature averaged 30 °C (Reicosky and Lindstrom, 1993), and under relatively dry soil conditions when considerably more soil aggregate breakup may have occurred. However, Al-Kaisi and Yin (2005) reported no significant difference in emission for MP, CP and NT shortly after tillage disturbance operations in their RC system. Similarly, La Scala et al. (2006) also found no significant difference in CO_2 emission for MP and CP in a time period of 24 h after tillage; the authors in that study in fact concluded that the impact of CP on the immediate CO_2 emission was as high as that caused by MP.

Relatively few studies have been conducted to directly compare the effects of MP, CP and NT on growing season CO_2 emissions from corn–soybean rotations in the Midwest. However, in this study the estimated cumulative seasonal emissions (CC: 6.4; RC: 5.5 Mg CO_2-C ha^{-1} $year^{-1}$) were similar to those reported for Iowa (Parkin and Kaspar, 2004) but greater than for fertilized and residue-amended soils in Ohio (Jacinth et al., 2002b; Jacinthe and Lal, 2004; Jarecki and Lal, 2006) and for the Great Plains (Kessavalou et al., 1998). In contrast, much greater CO_2 emissions have been reported for irrigated corn (Amos et al., 2005) and for continuous wheat (Frank et al., 2006), while Mosier et al. (2006) reported lower seasonal CO_2 emissions for no-till and conventionally-tilled corn–bean rotations.

We acknowledge the possible influence of our specific procedure and fixed duplicate anchor positions on the cumulative estimates of gas emissions in our research. Carbon dioxide fluxes from crop rows during the growing season derived mainly from shoot and root respiration of severely injured plants when plants are retained under the gas-sampling chambers, while emissions from the interrows (bare soil) reflected both soil and root respiration during the growing season (Kessavalou et al., 1998; Amos et al., 2005). Depending on plant growth stage, soil surface CO_2 emissions from within row areas have ranged from 10 to 198% of those from between row areas (Amos et al., 2005). In a recent study, Werth et al. (2006) found that total CO_2 efflux from soil planted to corn was substantially due to root respiration, and to a lesser extent due to microbial soil organic matter decomposition and rhizomicrobial (rhizosphere) respiration. In this study, growing season CO_2 fluxes were measured from a soil surface area that included both inter- and intra-crop row areas from which plant shoot material had been removed prior to sampling; therefore, seasonal CO_2 emission values reported here were attributed to both residue decomposition and root respiration but not to shoot respiration.

Different authors have arrived at different conclusions regarding tillage and rotation effects on growing season CO_2 emissions. However, in this study greater CO_2 emissions for CC contrasted Drury et al. (1998, 2004) who observed greater CO_2 emissions for RC relative to CC due to differences in soil aggregates. However, under corn rotation, Drury et al. (2006) reported that growing season CO_2 emissions were not significantly different among CP, fall zone-tillage and NT treatments on clay loam soils in Eastern Canada. Similarly, Mosier et al. (2006) found no differences of emissions from CC and corn–bean rotations under NT and MP systems.

Our lack of statistical differences in seasonal CO_2 emission among the tillage treatments was not unexpected. Ball et al. (1999) reported a lack of significant tillage systems effects on CO_2 emissions 3–4 weeks into the growing season. In contrast, Franzluebbers et al. (1995) found growing season CO_2 emissions to be greater under NT than conventional tillage in a Texas silty clay loam soil. Similarly, lower CO_2 emissions for NT relative to CP and MP was consistent with results from other seasonal experiments (Kessavalou et al., 1998; Dao, 1998; Bauer et al., 2006; Al-Kaisi and Yin, 2005) and this response has been attributed to greater surface crop residues for NT. Greater surface crop residues for NT probably served as a barrier for CO_2 emissions from soil to the atmosphere; surface residues may also reduce crop residue decomposition rate (due to reduced soil temperature and minimum soil-residue contact). Both factors may contribute to reduction of soil CO_2 emissions under NT (Reicosky et al., 1999). However, greater emissions for CP compared to MP in our research contrasted with results by Kessavalou et al. (1998), Bauer et al. (2006) and Dao (1998), and suggested that microbial decomposition of organic residues was higher for CP treatment in these soils. Perhaps CP systems like the one we employed re-distributed most surface residues rather evenly throughout mainly the upper half of the shank depth to which soil was disturbed. In contrast, our MP operation completely inverted the surface soil and residues down to the 22–25 cm depth where overall microbial residue decomposition might be slower because of the combination of higher soil moistures but lower soil temperatures relative to on or near the surface. In recent studies, significant SOC accumulation beneath at the 20–50 cm depth interval have been reported for long-term MP relative to NT and CP treatments; suggestive of a slower residue decomposition at greater depth and therefore, lesser CO_2 emission rate for MP (Yang and Kay, 2000; Deen and Kataki, 2003; Omonode et al., 2006). In these very same plots Gál et al. (submitted for publication) reported significantly more organic C accumulation in NT versus MP treatments close to the soil surface (27% higher SOC on a soil-mass-equivalent basis in the 0–30 cm interval), but substantially lower SOC in the NT than MP treatments deeper in the profile (32% lower on a soil-mass-equivalent basis in the 30–50 cm interval).

Based on the tillage and rotation system results with CO_2 flux of this study, we make three inferences. First, we speculate that the reason for the increased CO_2 flux observed in the CP system in our results is simply because of the closer proximity of crop residue in direct contact with the near-surface soil that represents the most dynamic zone responsible for residue decomposition. Second, perhaps CP treatment also provided greater aeration at deeper depths for root respiration particularly at the early stages of the growing season. Third, we also speculate that possible reasons for CC resulting in significantly greater CO_2 emissions (even though RC returned more biomass and biomass C during the corn year itself) were that CC returned more total biomass C over a 2-year period than the combination of soybean plus corn and that nitrogen fertilizers (and thus their stimulation of microbial residue decomposition) were applied annually in the CC sequence but bi-annually in the RC sequence.

4.3. Tillage practices and methane fluxes

Although CH_4 fluxes were not significantly affected by tillage and rotation treatments, the generally low values and net uptake of CH_4 reported in our study were consistent with those reported for cultivated soils (Chan and Parkin, 2001; Jacinthe and Lal, 2005; Venterea et al., 2005). Similarly, greater CH_4 uptake for CP (conservation tillage) relative to MP (conventional), and for CP and MP relative to NT treatment was consistent with Ball et al. (1999), Jacinthe and Lal (2005) and Venterea et al. (2005). In contrast, Kessavalou et al. (1998) reported a decrease in CH_4 uptake as soil disturbance increased (i.e. uptake was subsequently greatest for NT soils) in Nebraska. Higher CH_4 uptake for CP and MP relative to NT was attributed to increased soil disturbance and higher soil aeration resulting from CP and MP. Consequently, higher CH_4 uptake for CP re-affirmed our earlier observation that CP resulted in greater soil aeration and subsequent organic C and CH_4 oxidation from the near-surface layers. Similarly, consistent CH_4 emissions for NT were probably due to a combination of absence of soil disturbance, greater soil moisture and greater soil cover from crop residues (Jacinthe and Lal, 2005, 2004) which lead to more frequent anaerobic conditions, especially in the inherently poorly – but artificially drained – soils in our experiment.

5. Summary and conclusion

There is insufficient experimental data to accurately assess the effects of long-term tillage and rotation systems on greenhouse gas fluxes in the Midwest Corn Belt. This research was initiated to determine short- and seasonal fluxes of CO_2 and CH_4 in soils that have been uniformly managed using MP, CP and NT tillage practices in CC and RC for the last 3 decades. Short-term CO_2 emission measured for 168 h after fall primary tillage was higher for CP than for MP at all time of measurement. On a seasonal basis, CO_2 emission during the growing season was significantly affected by rotation (CC averaged 16% higher than RC), but not by tillage systems. However, among tillage systems CO_2 emission was numerically in the order: NT < MP < CP. Tillage and rotation had significant effects on methane fluxes in the short-term, but neither tillage nor rotation had significant effects on methane fluxes during the growing season. Although the soils were a net sink for CH_4, fluxes were generally very low and suggested that even 30 years of continuous NT did not significantly improve CH_4 uptake in these soils. Soil temperature and moisture effects on gas fluxes were significant, but specific relationships of temperature and moisture with gas emission were generally poor, and dependent on both seasonal timing of gas measurement as well as the tillage systems under consideration.

Our results suggested that the effects of fall primary tillage operations on gas fluxes are relatively short-lived, and that rotation system seemed to be a more important factor determining the dynamics of seasonal gas fluxes from the soil surface. Similarly, from a short-term perspective, since adoption of a NT management system will minimize soil disturbance and increase crop residue retention on the surface, NT is more effective in reducing greenhouse gas emissions compared to MP and CP. However, in the long term, CP may be more detrimental than MP systems in net CO_2 emissions while both CP and MP appeared to have an equally marginal effect on CH_4 uptake or loss in these dark prairie soils.

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